A Model of Hollow Cathode Plasma Chemistry

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- Existing Hollow Cathodes Have Limited Life
    - Longest duration hollow cathode failed after 3 years
    - Life limiting mechanisms:
        - Barium depletion
        - Orifice erosion or blockage
- High Fidelity Models Are Needed
    - 10 year life tests not practical
    - Life requirements must verified by short tests & analysis
    - Require detailed, predictive, 1st principles physics models
    - Must include all failure & performance degradation mechanisms
- JPL Hollow Cathode Model Development
    - Insert region plasma
        - 2-D model
        - Limiting results compared with published data
        - Barium ion transport
    - Orifice physics including erosion – 1-D model results
    - Thermal model and Keeper & beyond – coming soon!

Permanent Magnets

Magnetic Field

Ion Optics

Propellant Flow

Discharge Cathode

Propellant Flow

Anode

| − + | Discharge Supply |

| + − | Beam Supply |

Propellant Flow

| − + | Accelerator Grid Supply |

| + − | Neutralizer Keeper Supply |

Neutralizer Cathode

- Most ion thruster have two hollow cathodes
  1. Discharge cathode
  2. Neutralizer
- Planned NASA ion thrusters will use HC's
  - Flight experience is primarily with HC based ion thrusters
  - Present ion thrusters that use RF to ionize the propellant are much less efficient than ones using hollow cathodes
  - Propellant utilization efficiency is critical for future missions
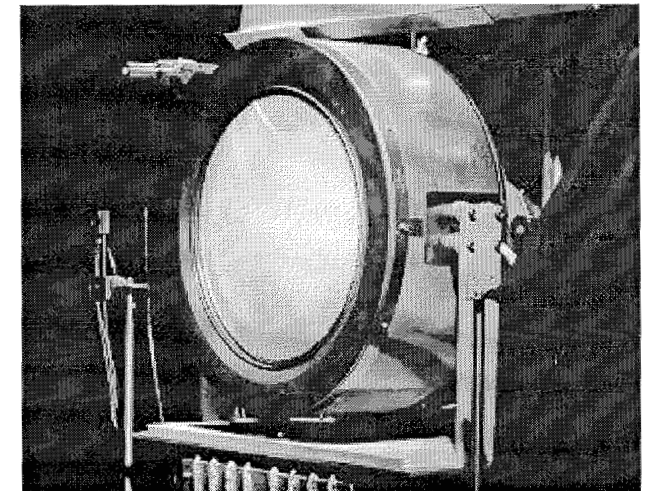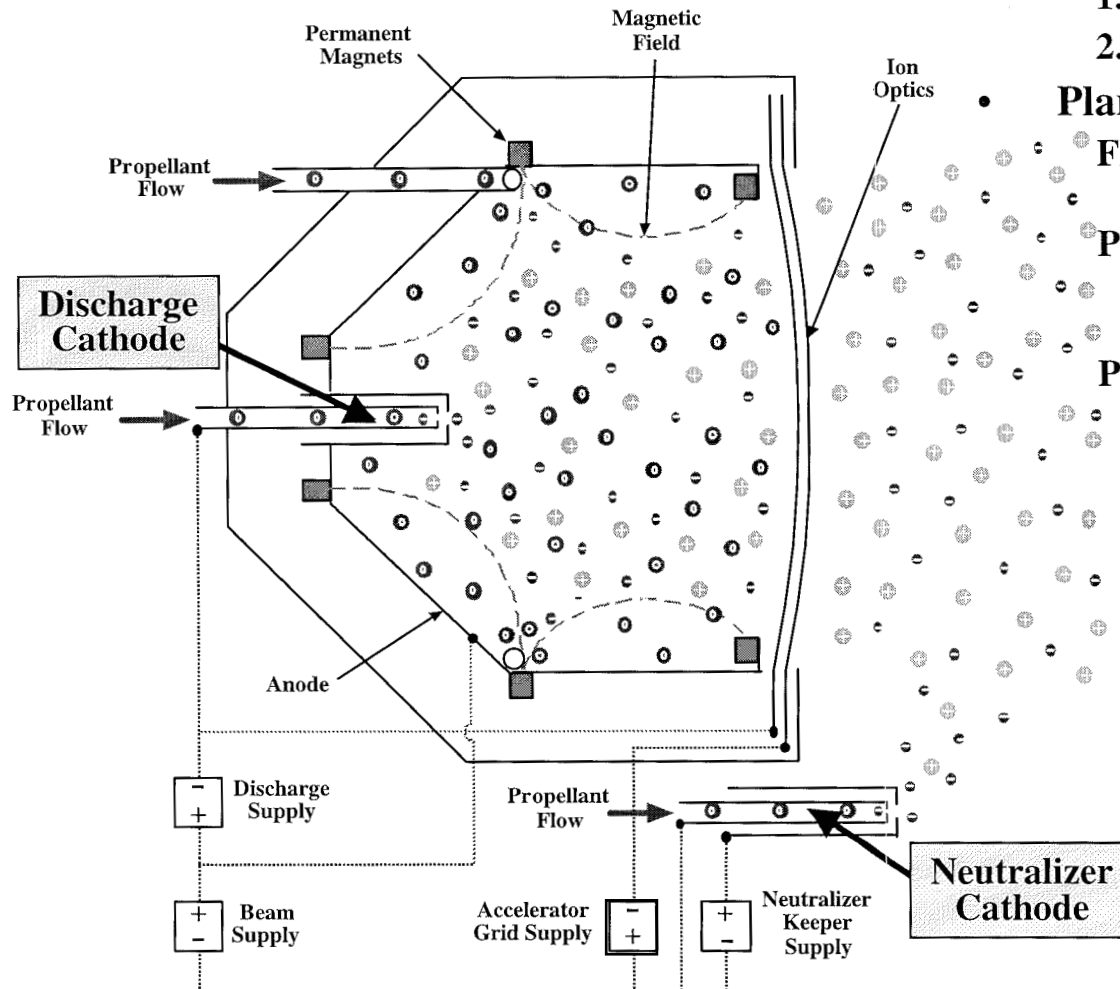

Engineering model ion thruster built by NASA GRC during 8200 hour endurance test at JPL.

- Hollow cathode provides a copious source of electrons
- Device partially ionizes a neutral gas
    - Input: typically propellant gas, e. g. Xenon
    - Output: electrons, ions, and unionized gas
- Electron current much greater than ions emitted
    - Electrons emitted from low work function Barium impregnated insert
    - Electron mobility >> Ion mobility
    - Electrons out >> Ions out
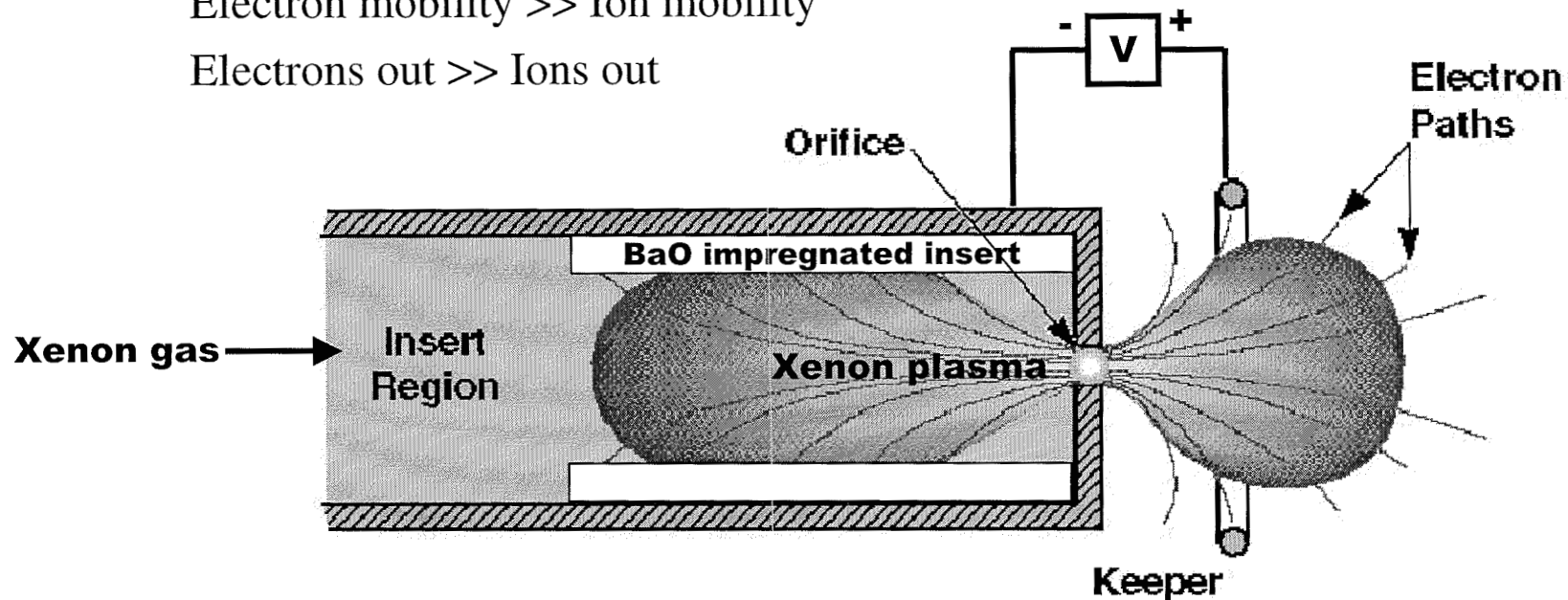
- Space Station Plasma Contactor Life Test
    - Longest test
    - Tim Sarver-Verhey, George Soulas, Mike Patterson, Scott Kovaleski
    - NSTAR like hollow cathode
    - Constant 13A emission current
- Hollow cathode failed to start after 3 years of operation
    - 23,776 hours - Starting voltage jumped from 50V to 725V
    - 28,000 hours – Failed to start
- Failure analysis
    - Free BaO and Ba depleted
    - Tungsten deposits on orifice plate
- Conclusion:

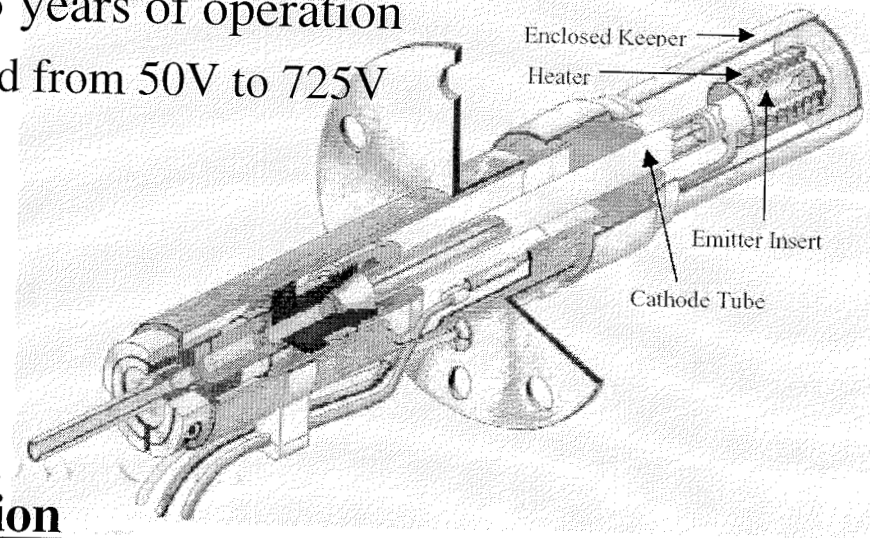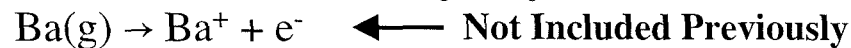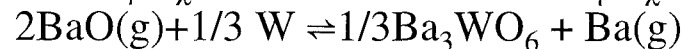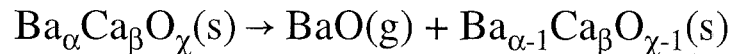**Failure Mechanism-Insert Depletion**

Figure 1. Drawing of a flight HCA (drawing not to scale).

Figure from "A Review of Testing of Hollow Cathodes for The International Space Station Plasma Contactor" S. D. Kovaleski, M. J. Patterson, G. C. Soulas, T. R. Sarver-Verhey, NASA Glenn Research Center, IEPC-01-271

Barium Ionization Reduces Insert Life

- Previous models of insert life based on equilibrium chemistry
  - Lipeles & Kan, Kovaleski
  - Observed Barium loss in EP hollow cathodes not much slower than vacuum cathodes.
- New model includes barium ionization

BaO-CaO-Al2O3 Phase Diagram

$$Ba_\alpha Ca_\beta O_\chi(s) \rightarrow BaO(g) + Ba_{\alpha-1}Ca_\beta O_{\chi-1}(s)$$
$$2BaO(g)+1/3\ W \rightleftharpoons 1/3Ba_3WO_6 + Ba(g)$$
$$Ba(g) \rightarrow Ba^+ + e^- \quad \longleftarrow \ \textbf{Not Included Previously}$$

- Ionization mean free path the order of a millimeter
  - Ba ionization potential   5.2eV   T insert   ~0.1 eV
  - Insert plasma $n_e \sim 10^{21}\ m^{-3}$ $T_e \sim 1$ eV
  - $\tau_{ionization} \sim 3 \times 10^{-6}$ sec
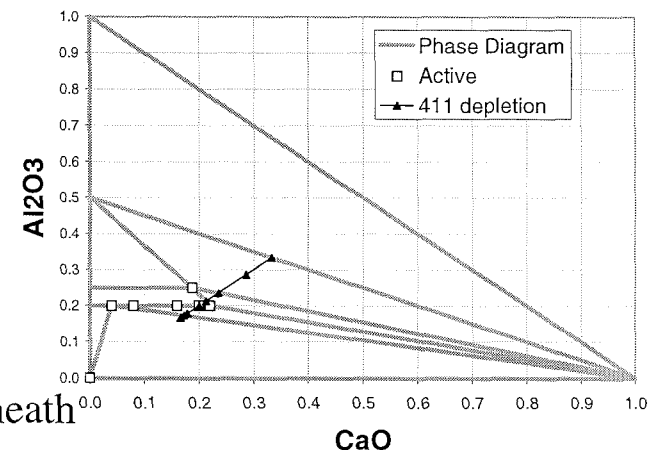 - Barium ions hit wall with ~10eV kinetic energy because of sheath
- Results
  - Very low barium neutral partial pressure in insert region
  - Barium loss rates greater than models assuming pressure equilibrium
- JPL lead team pursuing new hollow cathode designs that use proven traveling tube cathode techniques to increase insert life

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New Approaches For Hollow Cathode Inserts

Iridium-Tungsten Insert

BaO Dispenser

$$\sigma_{CEX} \approx 10^{-18} \, \text{m}^2$$

- New physical model – Ion transport dominated by charge exchange with neutrals

$$T \approx 1300 \, \text{K}$$

$$P \approx 10 \, \text{Torr}$$

$$n_0 \approx 7.5 \times 10^{22} \, \text{m}^{-3}$$

$$\ell_{CEX} = \frac{1}{n_0 \, \sigma_{CEX}} \approx 10^{-5} \, \text{m} \quad << \quad r_{insert}$$

- Reduces to ambipolar diffusion equation

$$-\nabla \bullet [D_a \nabla n] = \dot{n}$$

$$\frac{\partial^2 n}{\partial r^2} + \frac{1}{r} \frac{\partial n}{\partial r} + C^2 n = 0$$

- Neglecting axial variation, Bessel function zero sets upper bound on the electron temperature

$$C^2 = \frac{n_0 \sigma(T_e) \sqrt{\frac{8eT_e}{\pi m_e}}}{D_a}$$

- Comparison with data

  Malik, Montarde, and Haines, J. Phys D **33**, pp. 2307-2048, 2000
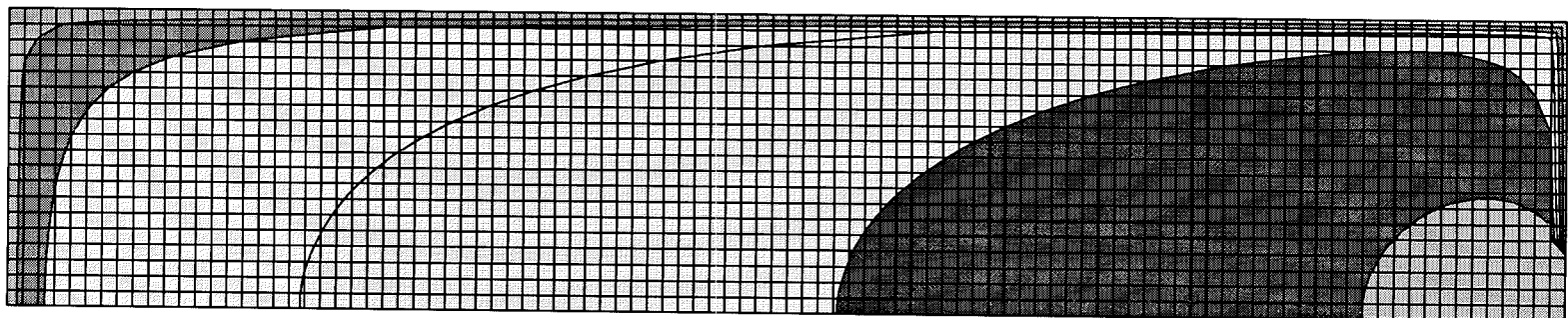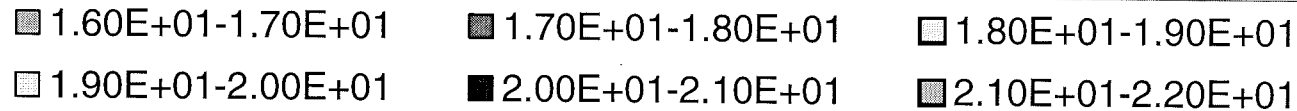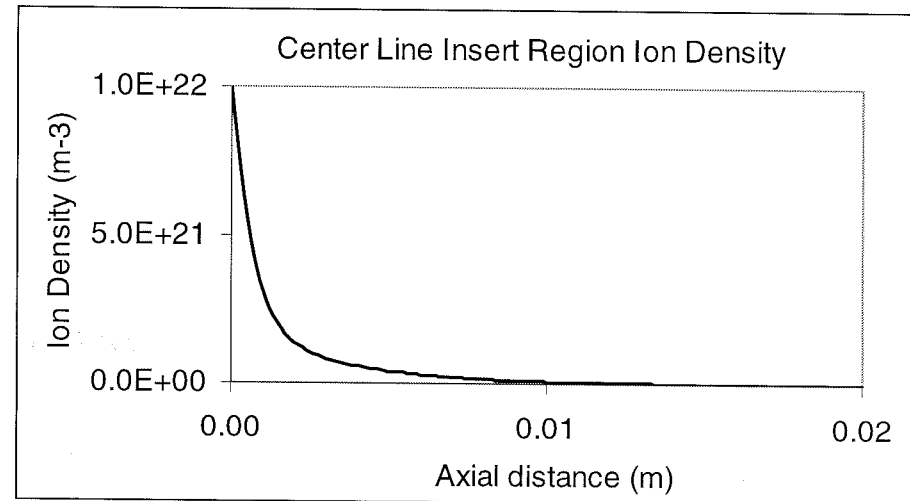
$$T_e^{data} = 1.1 \, eV$$

$$T_e^{theory} \approx 1.075 \, eV$$

Comparison probably fortuitously good!

Model predicts low ion current density to insert – average ion velocity << Bohm velocity

- Solution of ambipolar diffusion equation

- R-Z geometry

- Assumes constant T_e

- Ion density drops exponentially from orifice

Center Line Insert Region Ion Density

| 1.60E+01-1.70E+01 | 1.70E+01-1.80E+01 | 1.80E+01-1.90E+01 |
| 1.90E+01-2.00E+01 | 2.00E+01-2.10E+01 | 2.10E+01-2.20E+01 |

Gas flow →

Orifice

- The volume modeled includes the orifice and the chamfered region
- Extension of previous 0-D model
- Assumes quasi neutrality $n = n_i \approx n_e$
- Continuity equations

$$\pi R^2 \left(-\dot{n} + \frac{\partial u_0 \, n_0}{\partial z} \right) + 2\pi R \, u_{wall} \, n = 0$$
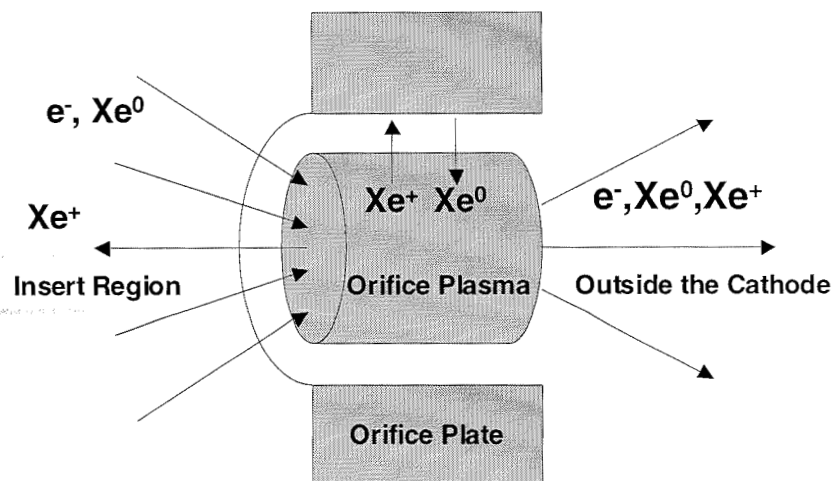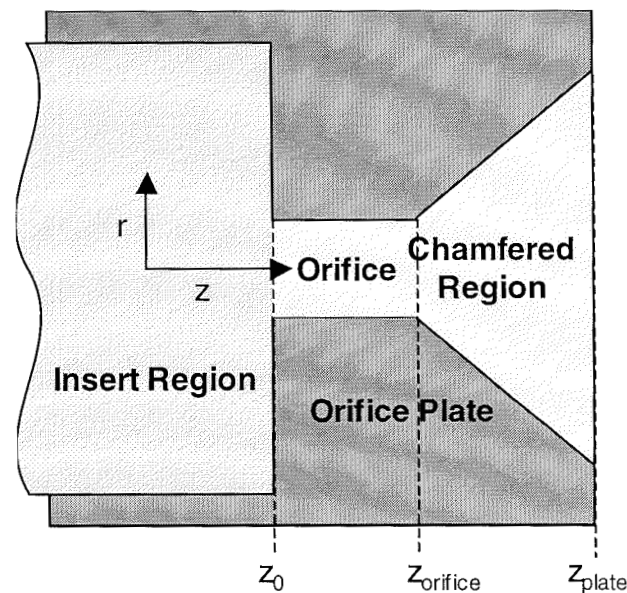
$$\pi R^2 \left(\dot{n} + \frac{\partial u_i \, n}{\partial z} \right) - 2\pi R \, u_{wall} \, n = 0$$

$$\pi R^2 \left(e\dot{n} + \frac{\partial j_e}{\partial z} \right) = 0$$

- Ion and electron momentum equations

$$n(u_i - u_0) = -D_i \frac{\partial n}{\partial z} + n\mu_i \, \mathbf{E}$$

$$j_e = e D_e \frac{\partial n}{\partial z} + e n \mu_e \, \mathbf{E}$$

- Electron temperature rises monotonically in orifice from insert region to chamfered region
- Ion density peaks in orifice
  - Ions flow back into insert region
  - Ions flow out toward keeper
- Ion diffusion approximation breaks down in chamfer region
  - Drop in neutral gas density
  - Region include for boundary conditions at orifice exit
- Ionization fraction ~ 10%

Electron Temperature

Ion Density in Orifice
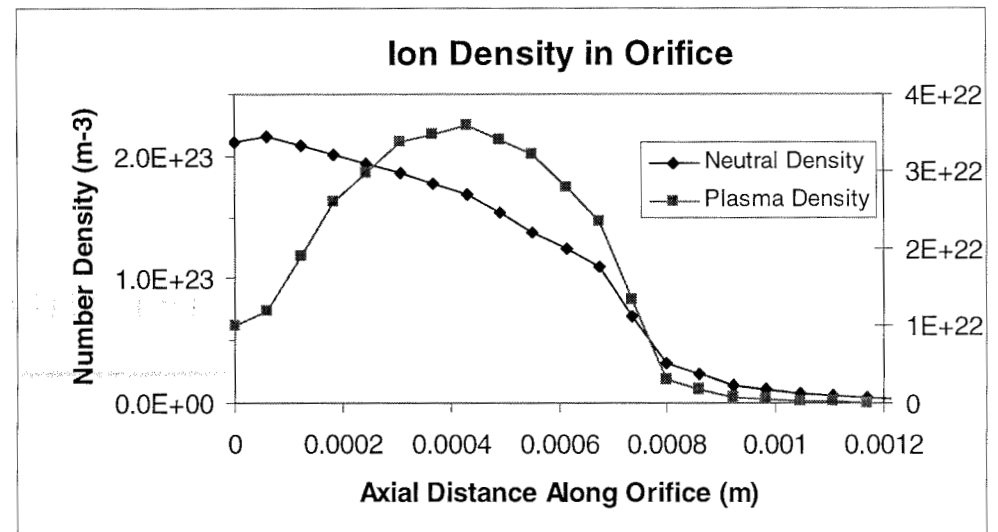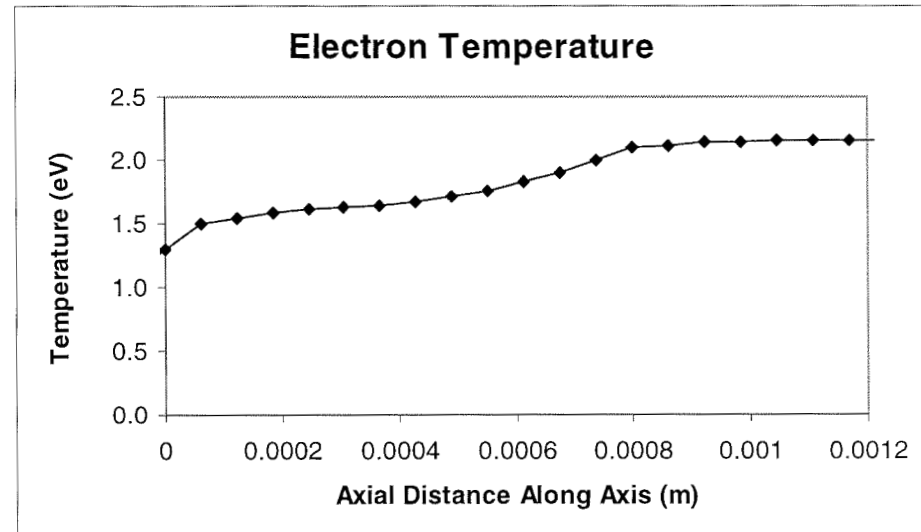
- Ionization contributes electrons to the current and ions to the wall

- Ionization contributes about an ampere to the current

- Ions impact to the walls probable orifice erosion mechanism

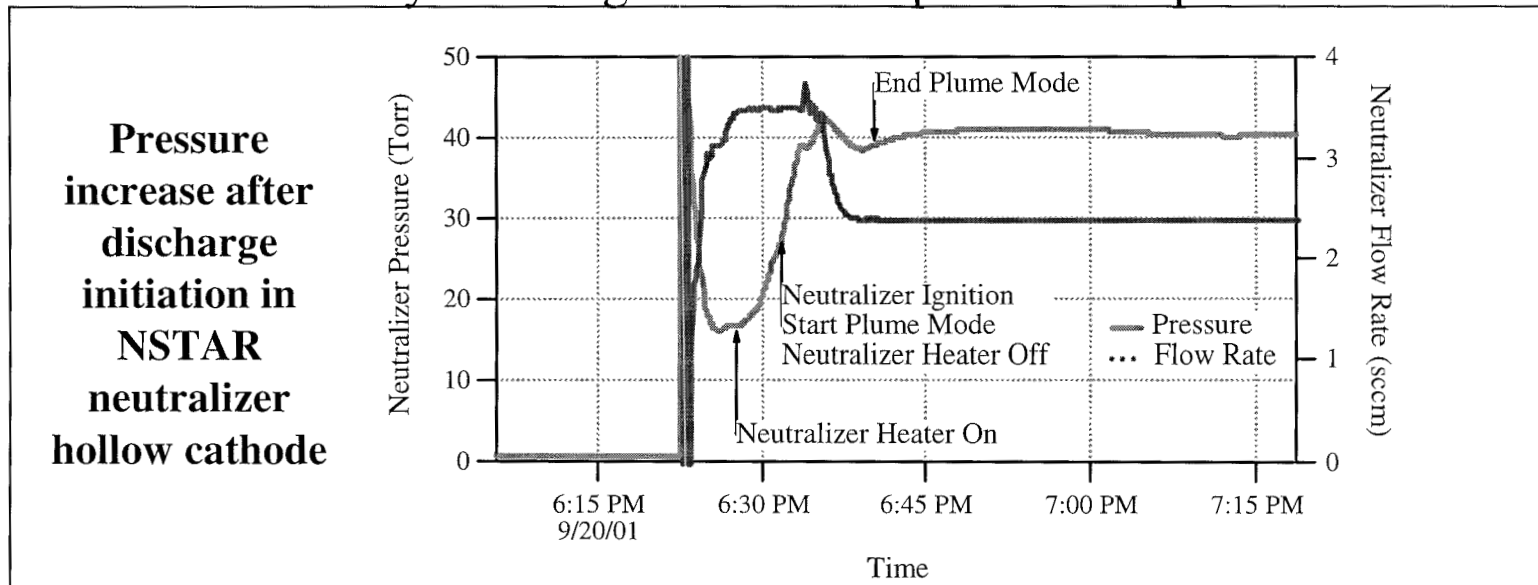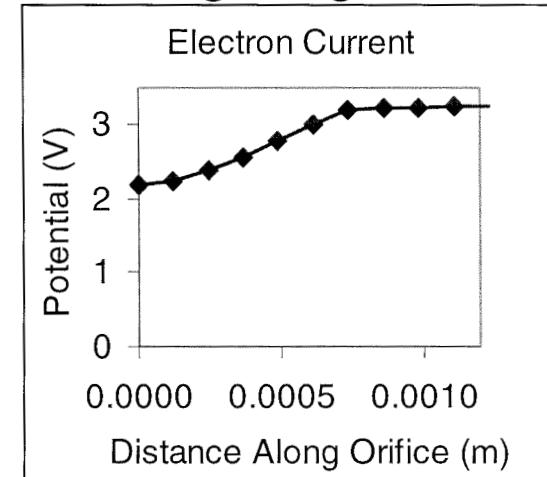- Power to the wall sum of ionization energy and ion kinetic energy including sheath

Ionization loss profile similar to observed orifice erosion data

Orifice Resistive Voltage Change

Ionization Power Loss
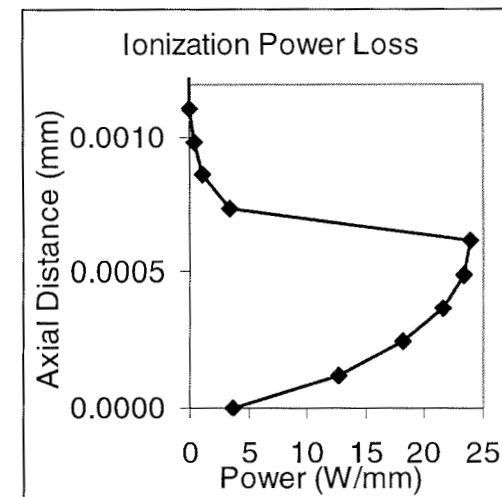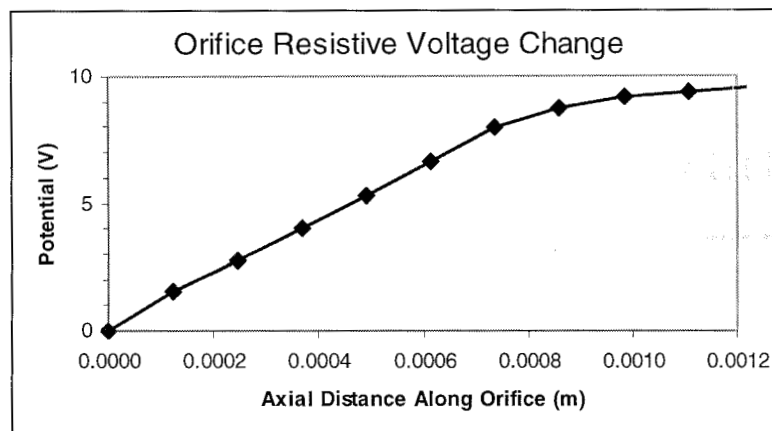
Model Results May Explain HC Pressure Rise

- Observation: Hollow cathode pressure rises when discharge is ignited
- Neutral flow between Poisseuille and Knudsen (Dan Goebel private communication)
- Inlet flow ~ 3.5 sccm
- Ionization currents to the walls ~ 1 Amp
- Ions that hit the walls come off as neutrals
- Neutral flow from recombination > 14 sccm
- Increased collisions with the wall acts as

increased viscosity resulting in increased pressure drop

Electron Current

Distance Along Orifice (m)

Pressure increase after discharge initiation in NSTAR neutralizer hollow cathode

- Model being developed to describe hollow cathode operation and wear mechanisms
  1. Insert chemistry
  2. Insert region plasma (1 & 2-D)
  3. Orifice and chamfer region plasma (1-D variable area)
- Early model results encouraging

  Barium ions transported upstream by electric fields

  Insert region electron temperature set by ambipolar diffusion

  Ionization profile in orifice region consistent with orifice erosion shape
- Planned Electric Propulsion Model Development at JPL

  Hollow cathode models

  Xe^{++} generation

  Combined insert & orifice 2-D model

  Thermal model including plasma effects

  2-D discharge chamber model

  Hollow cathode keeper region

  Magnetic field effects on transport

  Xe^{++} generation